

Performance of Filter Media as Function of Fibre Fineness in Pulse Jet Filtration System

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Abstract

Present investigation elucidates the role of pulse pressure and fibre fineness in the media on the emission and various pressure parameters (peak pressure, residual pressure and cake pressure). The individual as well as interaction effect of pulse pressure and fibre fineness on the media performance are very different as filtration process change from transient to steady state. Interaction effect among pulse pressure and fibre denier in media becomes very prominent with the passage of filtration time. The study also reveals that pulse pressure parameter is to be set in accordance to fibre fineness in the media keeping a balance between emission and operational pressure drop across the media.

Keywords

Cake Pressure; Fibre Denier; Peak Pressure; Pulse Pressure; Residual Pressure

Introduction

The environmental issue has become a major subject in the last few decades, affecting science and technology throughout the world due to the serious environmental impacts caused by industrial air pollution. Consequently, pulse-jet filtration has become the preferred choice all around the world, providing sound technical and commercially attractive solutions for successful operation of an industry integrated with pollution control equipment maintaining clean air requirements [1]. Pulse-jet fabric filters (PJFFs) are widely used to control the particulate matter emission and to recover the valuable particles in many industries like power generation, incineration, chemical, steel, cement, food, pharmaceutical, metal working, aggregate, and carbon black industries etc.

During filtration, gas passes from the outside to the inside of the cylindrical bags, held open by interior metal cages. The particles deposit on the external surface of the filter bags, thus allowing the clean air to pass through. With the particle deposition, a positive

effect is associated with greater filtration efficiency due to cake filtration, and on the other hand, a negative effect is associated with increased pressure drop. Since industrial filters encounter high-dust density (more than 250 g/Nm³), pressure drop increases steadily with time. Therefore, filter bags must be periodically regenerated, usually by pulse-jet cleaning. This operation involves injecting high-pressure back-pulse air (3–7 bar) into the filter bags for a very short time (50–150 ms). Back pulse dislodges dust cake from filter surface and then filtration process continues regularly so called on-line cleaning. During the filtration process, clogging and cleaning cycles of the operation results in the increase of total and residual pressure drop [2-5]. Peak pressure drop is often referred as total pressure drop; whereas residual pressure drop is defined as the pressure drop across the filter just after cleaning.

The residual pressure drop exceeds the pressure drop of the virgin filter element because of a residual dust layer, the occurrence of patchy cleaning, and/or the particles that have penetrated the filter medium and have not been removed by the cleaning action. Residual resistance is at a minimum when filtration process starts with a new fabric but reaches a stable value as the fabric is stabilized. Initial drag depends on various factors such as cleaning intensity, number of pulses, particle-size distribution, media structural characteristics and fabric slack. For a constant filtration velocity and inlet dust concentration, lower effective residual pressure loss usually represents a longer filtration time and a better cleaning effect. However, in the filtration process, the medium tends to be clogged internally, which is often considered 'irreversible'. The impossibility of dislodging many particles trapped within its depth is inevitable. Greater particle penetration into the medium occurred after each pulse-jet cleaning until saturation of the medium, corresponding to a balanced residual pressure condition. Thereafter, it is highly probable that the

surface mass profile would reveal only minor cycle-to-cycle variations [2,6].

In the process of filtration, pressure drop pattern is quite different from steady and unsteady processes. During filtration, pressure drop limits show a steep increase at the beginning (unsteady process) which is due to the embedding of dust inside the filter media because of depth filtration. As mentioned, even at the steady state, quite a small and imperceptible change takes place in the normal operational stage. Depth filtration is mostly replaced by surface- and cake-filtration, which has consequence that the deposited dust is removed more efficiently by the cleaning pulse. The residual pressure drop progression shifts with growing cycle time to smaller values but the bandwidth of total pressure drop minus residual pressure drop, that is to say the cake pressure drop, grows with increasing cycle time [7]. For steady state, the highest pressure drop is reached after a long operating time after which bags must be replaced. The increase rate of residual pressure drop during the filtration cycles is very important because it determines the lifetime of the filter bag. A medium is said to be blinded when cleaning fails to remove residual solids that are adhering or are embedded to it, so that its resistance to flow remains unacceptably high [8].

There are other implications of pressure drop across the system. Higher pressure drop during filtration indicates higher operational cost. The energy used by the fan accounts for 60–80% of the baghouse operation costs, and therefore, a stable and low differential pressure makes it worth investing in highly developed filter unit. This involves improved system design, judicious selection of filter media, and setting of operating parameters at the optimum level. During pulse-jet filtration, regulation of pressure drop is mainly accomplished through optimizing the impulse used and extent of cleaning of filter media in each cycle. Increase in pulse cleaning intensity can effectively reduce the differential pressure parameters across the bag. However, cleaning should not damage the bag filter while allowing filtration processes to operate at a steady and lowest possible pressure drop. Further, it is also necessary to conserve the dust layer up to a certain extent to ensure good filtration efficiency and, in certain cases, helps in absorbing gas on dust cake of specific properties. It may be added that energy used by the compressed air consumption

(due to pulse cleaning) is comparatively small (10-15%) to the total operating cost.

For effective filtration, filter medium has to be designed/ selected based on the application. The various filter media proposed for same application can have different flow rate characteristics and air-cleaning efficiencies. It is also important to note that the filtration requirements vary depending on the nature of aerosol. The media efficiency required for carbon black will probably not be needed for wood shavings [9]. While designing the filter fabric, it is often very difficult to meet the two contradictory requirements – the highest level of filtration efficiency and the minimum level of pressure drop. Improving the filtration efficiency of a fabric filter (through structural modification/higher material consolidation) leads to higher pressure drop for virgin filters. Sometime for meeting stringent particulate emission, higher filtration efficiency is chosen even at the cost of higher initial pressure drop.

Structural modification of the needle felt media is possible through changing fibre fineness. However, the studies relating to the influence of fiber fineness on media performance are very limited. The fibers are normally in the range of 1.66– 3.33 decitex, though trends of considerably finer ‘microfibers’ (e.g. less than 1 decitex) have gained some prominence. However, in a study, use of coarser fiber (7 denier) instead of 2.7 denier/3 denier fiber in PPS felt has been found to improve the performance of a hybrid filter unit (COmpact Hybrid PArticulate Collector – COHPAC) as permeability increases substantially without compromising particulate collection efficiency. Continuous cleaning resulting from heavy ash accumulation has not been a problem unless the performance of the upstream hot-side electrostatic precipitator degrades [10]. However, the general trend is to use finer fiber for achieving higher filtration efficiency. Some manufacturers adopted layer fabric concepts [11] with high particle-collection efficiency fibers on the surface whilst retaining coarser, less expensive fibers on the back for maintaining lower pressure drop without compromising the filtration efficiency.

Apart from fabric selection, a successful pulse cleaning of the filter is clearly essential to reach a low and stable conditioned pressure drop and to operate the filter over long periods. In pulse jet cleaning, combination of injecting pulse pressure (initial tank pressure) with valve opening time (total air volume released) with

pulse cleaning cycle time is the factors governing critical cleaning force for cake dislodgement. However, performance of an inappropriate filter element cannot be improved by increasing pulse frequency and pressure as both will lead to mechanical damages to the filter bag leading to shorter bag life [2]. Very recent studies [12,13] shows that out of the aforesaid pulse cleaning factors, pulse pressure is the most critical factors governing emission and all pressure parameters. Although pulse pressure reduces the pressure differential across the fabric but it also increase the level of emission.

In view of the above background, present study is intended to investigate the influence of fibre fineness upon the media performance during pulse jet filtration process. For process optimization, it is also required to set the process in tune with media characteristics. Pulse pressure at the time of pulse cleaning operation is also studied in conjugation with media type for analysis of media performance under varied situations. Interactive and comprehensive study of the aforesaid parameters with aspect of their contribution on filtration performances is necessary to satisfy separation norms at lower running cost.

Experimental

Materials

Two nonwoven needle felt samples were prepared using 100% polyester fiber of 1.4 denier and 2.0 denier. The fabrics were pre-needled with 20 punches/cm² and the final needling was done alternatively on each side of the fabric (first needling from top then from bottom and finally from top). After final needling, calendaring of all the fabrics was done. The machine speed, needle density on the board and the strokes per minute were chosen in such way so as to obtain required punches density of 200 punches/ cm². The final fabric weights (GSM) were kept same of the 385 g/m² for these two denier samples. The fabric porosity of the two types of fabric is 87.5% and 90.7% respectively for 1.4 denier and 2.0 denier fibre fabrics. For experimental run, filter bags were made from two different types of filter media. Length and diameter of filter bags used were 1.2 and 0.12 m respectively; and total surface area of single bag was 0.46 m².

Experimental procedure based on orthogonal design

The experiment was conducted using pilot plant filtration unit (Fig. 1) embedded with pulse-jet

filtration system. The filter unit is designed based on simulated condition as operations of industrial bag house. It consists of aerosol feeding zone, draft zone, filter unit zone and pulsing zone. Inside the filtration unit, 4 bags are placed in two rows (two bags in each row).

For the conduct of experiment and also for statistical analysis [L₄ (2³)] orthogonal design methodology was adopted. The design array involves two factors, each of two levels (Table 1) for investigation of the impact of pulse pressure and media fiber denier on the clean gas concentration and differential pressures (ΔP) in progression of time. Four different combinations/running with two factors in accordance to orthogonal design array are given in Table 2. The basis of this specific orthogonal array is based on linear graph as indicated in the Figure 2. The linear graph indicates the concept of the interaction among pulse pressure and media fibre denier which has been conceived during experimentation. It may be noted that the design plan is similar to that of full factorial design. The whole experimental run is repeated for replication. Replication permits estimation of experimental error; otherwise error degree of freedom is zero in the present design concept. Further through replication more precise estimation of regression and ANOVA is possible.

During the experiment apart from two factors, the other parameters such as volumetric air flow (1.64 m³/min) and dust concentration (85.1 g/m³), tank gauze pressure (200 KPa), nozzle diameter (20 mm), distance between filter opening and nozzle (30 mm), pulse duration (100 ms) and cleaning pulse cycle time (54 sec) are kept as fixed factors during experimental runs. All four experimental run are performed in a random order as of 1, 3, 4 and 2. Reason for randomization is for effective statistical analysis through unbiased estimation of the impact of factors and for validity of inference drawn. Further to this normal probability plot is used to evaluate the normality of the distribution of the output parameters. From the normal probability plots, it is found that the residuals for each output parameters fitted close to the normal distribution which validates the design of experiment followed by statistical analysis.

In the study pulse cleaning process is governed based on cleaning at constant time interval. Considering 10 rows of industrial bag house, a pulse time interval of t s between two rows of bag will result in a cycle time interval of $9t$ s for each row of bag. In the present work,

as the pulse time interval for two rows of bag was taken fixed i.e. 6 sec, therefore total cycle time for regeneration was 54 sec. All runs are continued for four hour filtration process with constant inlet dust feeding (85.1 g/m³). During filtration, filter media is challenged with 33.6 kgs of cement dust in four hour run. During filtration time, continuous data acquisition for pressure drop (ΔP) in each 0.5 sec was done by ABB pressure transducer and recorded all data of pressure differential across filter bags and also at the same time a graph *Time Vs. ΔP* showed on ABB Field mountable video graphic recorder. It was found that differential pressure drop (ΔP) become almost stable after half an hour in all runs. Cleaning peak pressure and residual pressure directly obtained from the recorded data. Cake pressure is derived as it is the difference between peak pressure and respective residual pressure data. After three hour filtration-process, downstream emission was measured based on 1 hour collection of particulate matter by stack sampler [13] which provides the assessment about the amount of emitted particles per unit volume and accordingly calculated the dust concentration. Table 2 shows the data of emission and pressure drop at different experimental run.

The ANOVA technique was conducted to reveal the effect of individual factors on filtration performance and emitted particulate size distribution and *F* ratio and percentage contribution of different factors were studied. From the ANOVA analysis, % contribution of different factors was evaluated based on the following expression.

$$\text{Factor \% contribution} = (SS_f - df_f \cdot V_e) / SS_T,$$

Where, SS_f = Sum of square of the factor,

df_f = Degree of freedom of the factor,

V_e = Mean square of pooled error, and

SS_T = Total sum of squares.

Finally regression equations were derived with all the main factors for the output performance like downstream outlet dust concentration, peak pressure, residual pressure, and cake pressure for graphical presentation of data.

Results and Discussion

On dust concentration

Downstream dust concentration increases with the increase in both pulse pressure and media fibre denier

(Table 3, Fig. 3). Higher pulse pressure significantly controls direct particle penetration mechanism since the media remain unprotected at the time of cleaning. Earlier studies also highlighted that just after the cleaning, the penetration is high due to straight through penetration [14,15]; consequently particles smaller than the fabric pore size escapes till the time pore bridging starts during online filtration process. Higher filtration efficiency in case of filter media made out of finer fibre (lower denier) is due to greater specific surface area of finer fibers, higher level of consolidation (fiber flexibility coupled with barb needle to take up more fiber during downward stroke in the needle punching process), and feasibility of achieving a smaller size of theoretically defined pores. It is also observed that both pulse pressure and denier have dominant individual impact (41.4% and 55.3% respectively), but their interaction effect is quite small (2.7%) (Table 4).

On pressure parameters

In general, all the pressure parameters (peak pressure, residual pressure and cake pressure) decrease with the increase in cleaning pulse pressure (higher cleaning intensity) and fibre denier in the media (Table 3, Fig. 4 - 9). Further, at any level of pulse pressure and fibre fineness, all the aforesaid pressure parameters increase significantly from unsteady state to steady stage. At the transitory stage role of peak pressure is vital (86%) in regulating peak pressure; whereas the contribution of fibre fineness is relatively small (11.7%) and its interaction with pulse pressure is insignificant (Table 4). With the passage of time and at the steady state role of fibre fineness and its interaction with pulse pressure increase significantly. Due to interaction effect, impact of fibre fineness on peak pressure is different at different level of pulse pressure (Fig. 5). At lower pulse pressure, peak pressure drops largely with the increase in fibre denier; whereas change in peak pressure is quite insignificant at higher pulse pressure.

Residual pressure drop across the media also follows similar trend to that of peak pressure with the increase in pulse pressure and fibre denier (Fig. 6-7). Unlike peak pressure, role of denier on residual pressure is quite significant even at the transitory state (Table 4). At the initial stage, media is relatively free from dust, therefore fabric structure might play a very significant role. Higher fabric porosity in case of coarser denier fibre fabric will cause less resistance to air resulting lower residual pressure drop. With the passage of time, interaction effect among fibre fineness and pulse

pressure increase significantly similar to the case of peak pressure. It implies that the role of dust – fabric interaction becomes prominent at steady state of filtration operation.

Similar to the above pressure parameters, cake pressure drop decrease with the increase of either pulse pressure or fibre denier in the media (Fig. 8-9). At the beginning role of pulse pressure is very prominent without any significant interaction effect with the fibre fineness (Table 4). Interaction effect increases significantly at the steady state of filtration operation. It is important to note that at steady state and for the coarser fibre media, all the pressure parameters are least affected with the change of pulse pressure. This implies that pulse pressure can be set at lower level for the media made up of coarser fibre and vice versa. This will result in lower operating pressure drop which is beneficial for lower energy consumption and long time running performance of the filter. However, dust concentration level should be within permissible limit while using either finer or coarser fibre materials.

Conclusions

Based on the investigation into the role of pulse pressure (cleaning parameters) and fibre fineness in filter material on emission and on the various pressure parameters across the filter media, the following conclusions have been made:

- Outlet dust emission is predominantly affected by the individual effect of pulse pressure and fibre denier in filter media.
- All the pressure parameters (peak pressure, residual pressure and cake pressure) decrease with the increase in cleaning pulse pressure (higher cleaning intensity) and fibre denier in the media. Further, at any level of pulse pressure and fibre fineness, all the aforesaid pressure parameters increase significantly from unsteady state to steady stage.
- Interaction effect among pulse pressure and fibre denier in media becomes very quite large with the passage of filtration time. This implies that the role of dust – fabric interaction on various pressure differentials becomes prominent at steady state of filtration operation.
- At steady state, pulse pressure can be set at lower level for the media made up of coarser fibre and vice versa. This will result in lower operating

pressure drop which is beneficial for lower energy consumption and long time running performance of the filter. However, dust concentration level should be within permissible limit while using either finer or coarser fibre materials.

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TABLE 1 FACTORS OPERATING VALUES CORRESPONDING TO CODED LEVELS

Factors Levels	Pulse pressure (bar)	Filter media fineness (denier)
Level : 1	2 bar	1.4
Level : 2	3 bar	2.0

TABLE 2 ORTHOGONAL EXPERIMENTAL L₄(2³) DESIGN PLAN AND CORRESPONDING RESULTS

Run no.	Factor levels			Operation I						Operation II					
				Pulse pressure	Filter media denier	Dust conc., mg/Nm ³	Peak pressure (ΔP), Pa, 1/2 hr.	Peak pressure (ΔP), Pa, 1/2 hr.	Residual pressure (ΔP), Pa, 1/2 hr.	Cake pressure (ΔP), Pa, 1/2 hr.	Dust conc., mg/Nm ³	Peak pressure (ΔP), Pa, 1/2 hr.	Residual pressure (ΔP), Pa, 1/2 hr.	Cake pressure (ΔP), Pa, 1/2 hr.	Cake pressure (ΔP), Pa, 1/2 hr.
1	1	1	1	68.16	27.8	27.8	426.39	49.82	284.39	18.34	142.00	65.23	47.19	298.20	150.29
2	1	2	2	62.37	92.7	92.7	124.25	39.42	78.94	22.95	43.31	61.25	38.37	87.25	51.39
3	2	1	1	51.88	85.2	85.2	112.19	41.87	77.37	10.00	34.81	53.87	43.12	80.57	39.32
4	2	2	2	48.15	126.9	126.9	104.44	33.83	69.43	14.32	35.01	46.54	31.51	68.39	42.85

TABLE 3 REGRESSION EQUATIONS RELATING FILTRATION PARAMETERS

Outlet dust parameters	Regression equations	R ²	SE
Outlet dust concentration (mg/Nm ³)	-120.2 + 83.0 Pulse pressure + 90.4 Denier – 24.0 Pulse pressure. Denier	0.98	4.14
Peak pressure, Pa, ½ hr.	84.8 -13.2 Pulse pressure - 4.2 Denier – 0.65.Pulse pressure. Denier	0.98	1.43
Peak pressure, Pa, 4 hr.	1362.6 - 619.2 Pulse pressure - 603.8 Denier + 297.8 Pulse pressure. Denier	0.99	10.0
Residual pressure, Pa, ½ hr.	63.6 - 5.8 Pulse pressure - 9.4 Denier – 0.2 Pulse pressure. Denier	0.97	1.36
Residual pressure, Pa, 4 hr.	910.0 - 410.5 Pulse pressure - 406.3 Denier + 198.1 Pulse pressure. Denier	0.99	5.82
Cake pressure, Pa, ½ hr.	20.9 -7.4 Pulse pressure + 5.2Denier – 0.4 Pulse pressure. Denier	0.99	0.38
Cake pressure, Pa, 4 hr.	454.7 - 209.7 Pulse pressure - 199.0 Denier + 100.7 Pulse pressure. Denier	0.98	5.19

TABLE 4 ANOVA RESULTS AND FACTOR CONTRIBUTIONS TO FILTRATION PERFORMANCES

Factor	F(calculated)			Factors, % contributions		
	Pulse pressure	Denier	Interaction pulse pressure and denier	Pulse pressure	Denier	Interaction pulse pressure and denier
Outlet dust concentration, mg/Nm ³	257.6	344.2	16.7	41.4	55.3	2.7
Peak pressure, Pa, ½ hr.	195.4	26.5	0.1	86.0	11.7	0.04
Peak pressure, Pa, 4 hr.	594.5	493.0	422.9	38.7	32.1	28.9
Residual pressure, Pa, ½ hr.	40.0	101.0	0.01	27.6	69.7	0.01
Residual pressure, Pa, 4 hr.	757.4	7023.2	579.5	37.1	34.4	28.4
Cake pressure, Pa, ½ hr.	888.7	280.7	0.6	75.7	23.9	0.05
Cake pressure, Pa, 4 hr.	255.9	174.1	187.8	41.1	28.0	30.2

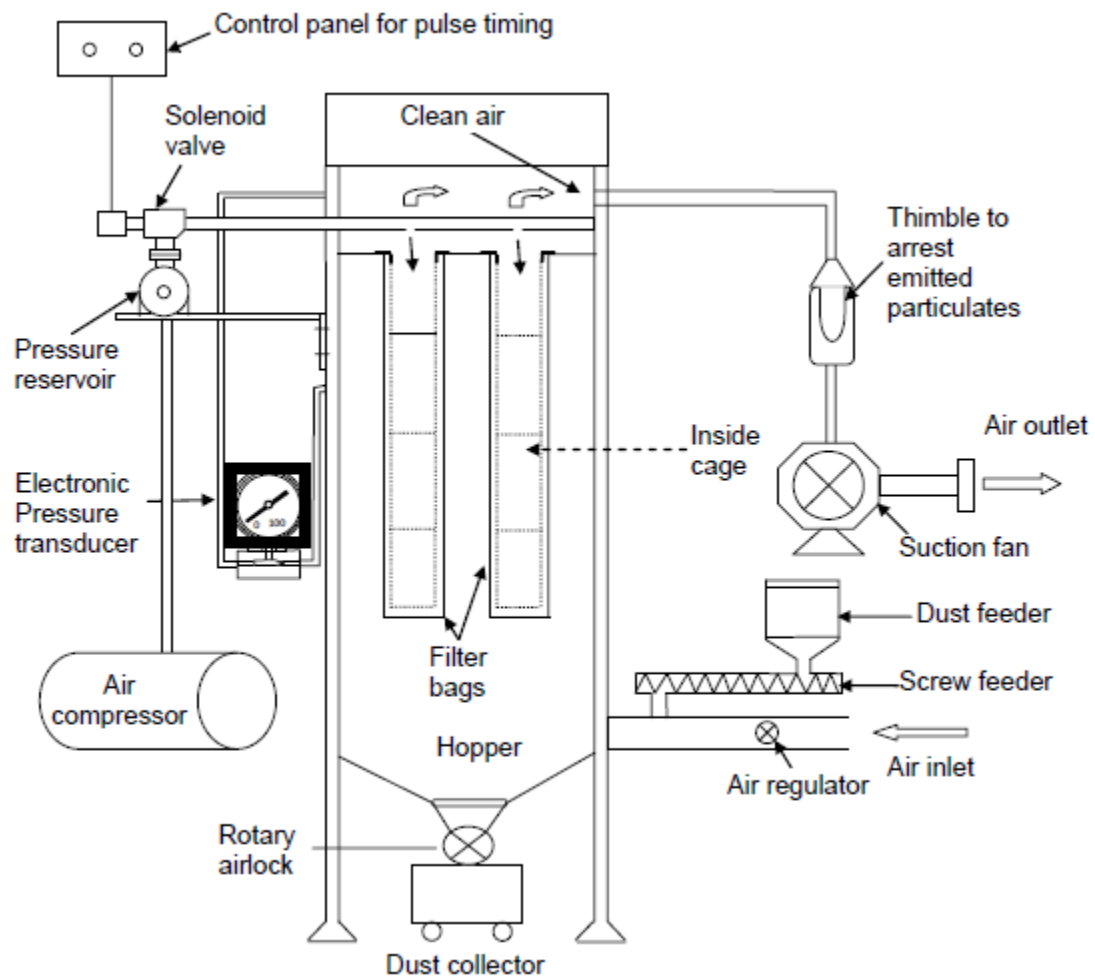


FIG. 1 THE SCHEMATIC DIAGRAM OF FILTRATION EQUIPMENT

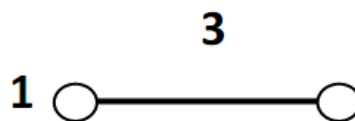


FIG. 2 LINEAR GRAPHS OF FACTORS INVESTIGATED (1-PULSE PRESSURE, 2-MEDIA FIBRE DENIER, 3-INTERACTION AMONG PULSE PRESSURE AND FIBRE DENIER)

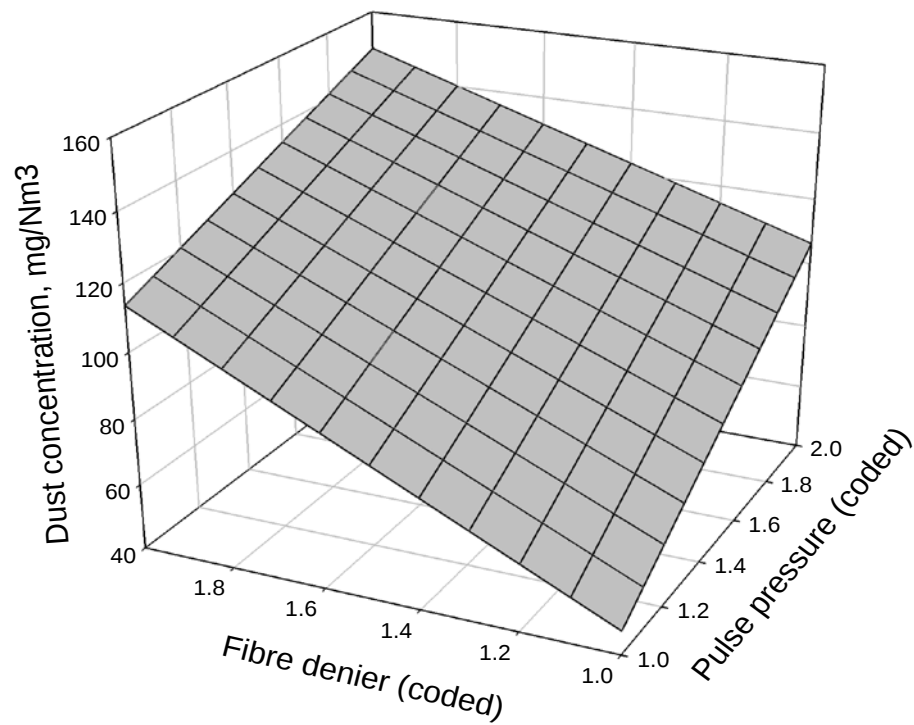


FIG. 3 EFFECT OF PULSE PRESSURE AND FIBER DENIER ON DUST CONCENTRATION

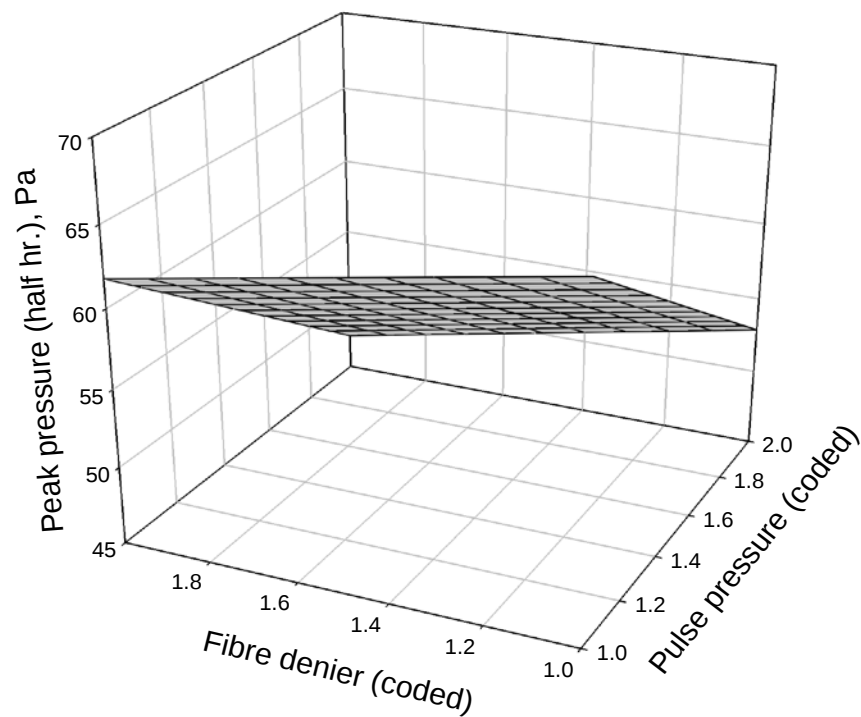


FIG. 4 EFFECT OF PULSE PRESSURE AND FIBER DENIER ON PEAK PRESSURE (HALF HR.)

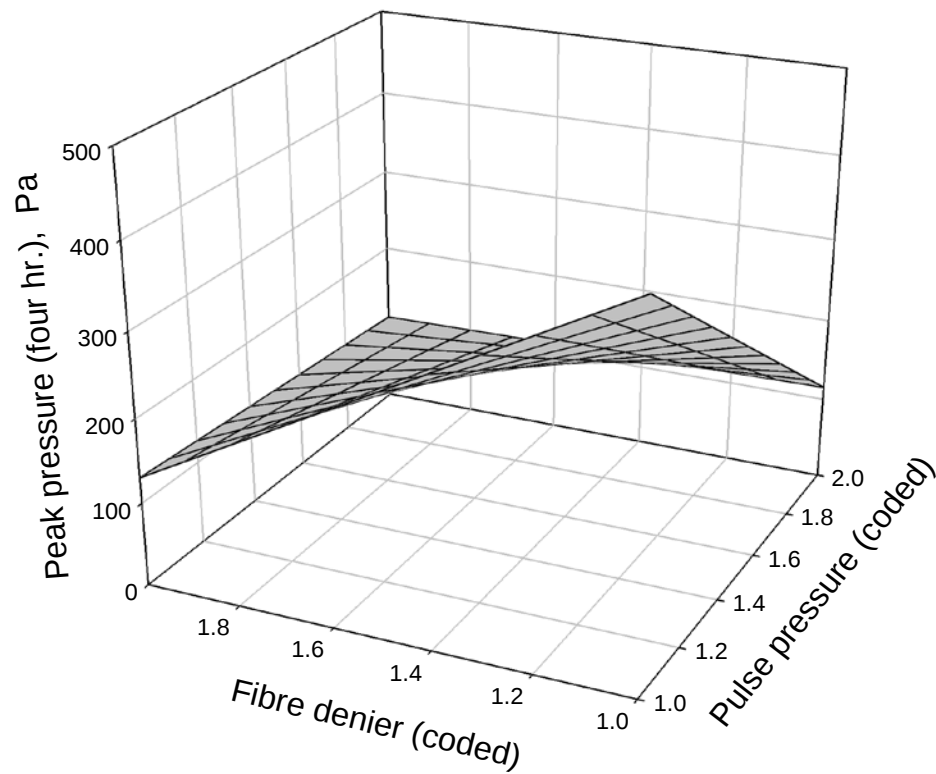


FIG. 5 EFFECT OF PULSE PRESSURE AND FIBER DENIER ON PEAK PRESSURE (FOUR HR.)

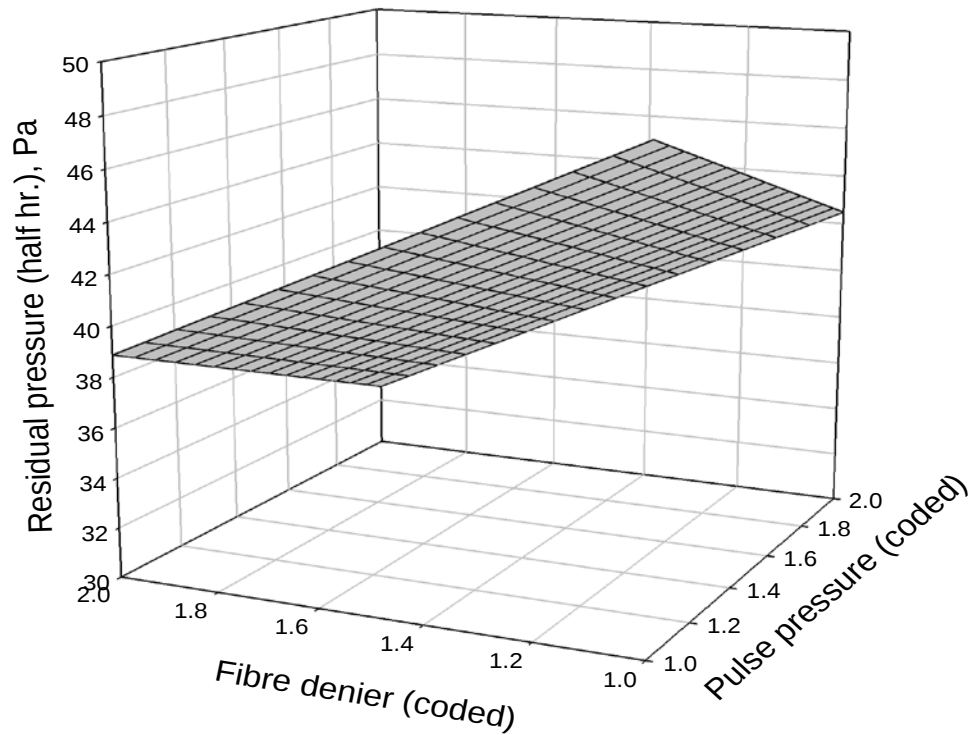


FIG. 6 EFFECT OF PULSE PRESSURE AND FIBER DENIER ON RESIDUAL PRESSURE (HALF HR.)

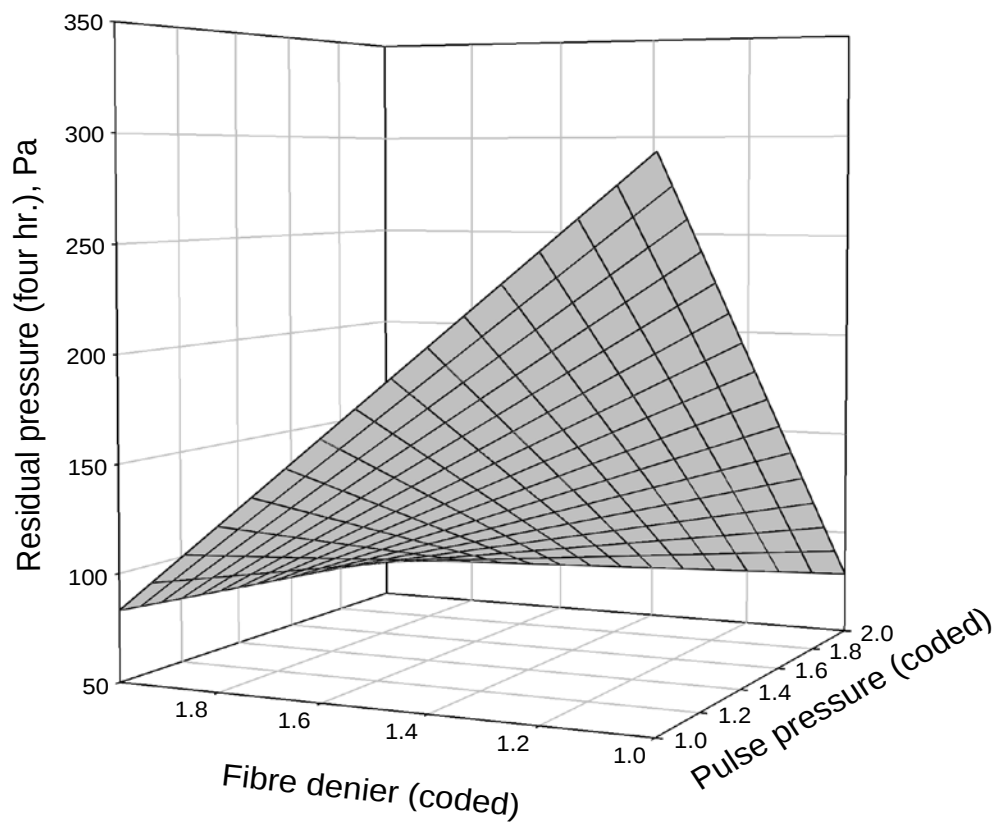


FIG. 7 EFFECT OF PULSE PRESSURE AND FIBER DENIER ON RESIDUAL PRESSURE (FOUR HR.)

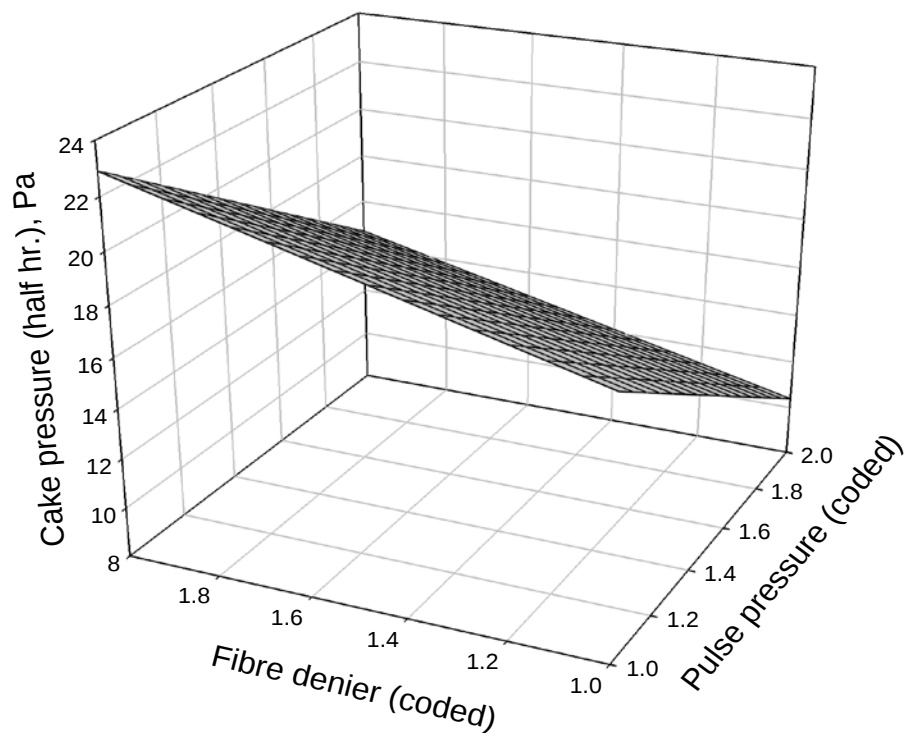


FIG. 8 EFFECT OF PULSE PRESSURE AND FIBER DENIER ON CAKE PRESSURE (HALF HR.)

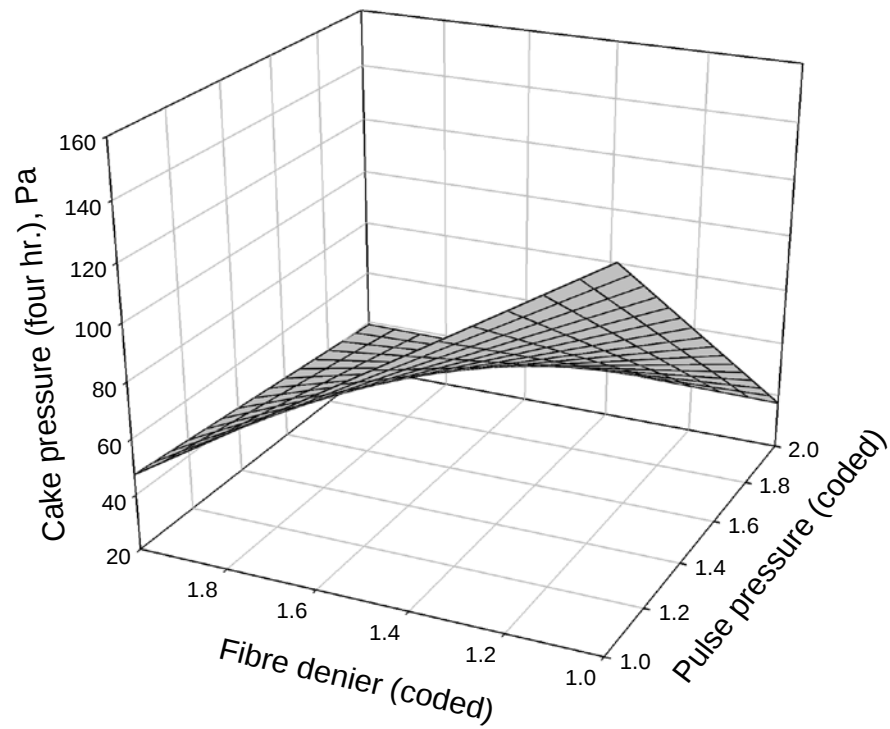


FIG. 9 EFFECT OF PULSE PRESSURE AND FIBER DENIER ON CAKE PRESSURE (FOUR HR.)